MAE-3038

RESEARCH ON INTEGRATION OF AIRBORNE HAZARD ALERTS WITH ADVANCED AIR TRAFFIC MANAGEMENT AND CONTROL

FINAL REPORT
FAA Grant No. 92-G-0011
Princeton Account No. 150-6649

February 11, 1999

Prepared for:

FEDERAL AVIATION ADMINISTRATION TECHNICAL CENTER
Atlantic City, NJ 08405

Robert F. Stengel
Professor
Principal Investigator

ABSTRACT

System requirements for integrating airborne, ground-based, and space-based systems devoted to enhanced air traffic management were defined. The time frame of interest is well beyond the normal range of existing programs and activities, focusing on air transport operations near the end of the first quarter of the next century (c. 2025). It was assumed that a full range of navigation aids, advanced sensors, and parallel-processor computers consistent with the then-current state-of-the-art would be available for use in the National Airspace System. A central purpose was to identify targets for the evolutionary development of integrated airborne, ground-based, and space-based flight/traffic management systems that maximize the efficient use of airspace while retaining a high level of safety for all-weather aircraft operations.

The period of performance for this contract was July 15, 1992 to July 14, 1996.

TABLE OF CONTENTS

ABSTRACT i

1. STATEMENT OF THE PROBLEM 1

   1.1 Advanced Air Traffic Management: The Intelligent Aircraft/Airspace System 1
   1.2 Wake Vortex Encounter 2

2. SUMMARY OF RESULTS 3

   1.1 Advanced Air Traffic Management: The Intelligent Aircraft/Airspace System 3
   1.2 Wake Vortex Encounter 4

3. LIST OF PUBLICATIONS AND PRESENTATIONS 6

4. LIST OF PARTICIPATING SCIENTIFIC PERSONNEL 8

5. INVENTIONS 8

1. STATEMENT OF THE PROBLEM

1.1 Advanced Air Traffic Management: The Intelligent Aircraft/Airspace System

Today's air traffic management system has been shaped by the evolution of equipment for computation, communications, surveillance, and navigation, and that trend will continue. In the near term, systems for collision avoidance, satellite-based navigation and communications, and on-board flight management provide modern airliners with new capabilities. A perfect air traffic management system unfettered by cost and political constraints would allow unimpeded air travel for passengers and freight on demand, with zero delays, complete safety, minimal fuel use, and low environmental impact, all of this occurring in any weather. It would be totally transparent to aircraft operating personnel while providing adequate safeguards for air traffic managers. It would be an *Intelligent Aircraft/Airspace System* (*IAAS*), in which potentially conflicting needs for autonomous vehicle operation, assured separation, and seamless terminal operations are satisfied by shared knowledge, massive computational support, cooperative control, and failure-tolerant systems.

Two tasks were addressed. The first was an assessment of technology relevant to an *Intelligent Aircraft/Airspace System* that could be implemented several decades hence, with particular emphasis on the integration of airborne, ground-based, and space-based systems. The second took a more general look at alternative structures for intelligent control and estimation for large-scale systems.

Generic technologies for sensing, computing, and communication were examined, with the goal of establishing baselines for this program. *Three scenarios* included a baseline reflecting the most likely evolution of technology, bracketed by higher and lower scenarios that account for uncertainties in development. Where appropriate, alternatives for solving particular problems in hazard alert, navigation, communication, and surveillance were identified, and the consequences of adopting each approach were noted. Special attention was paid to areas in which airborne and ground-based capabilities are likely to overlap.

Methods for acquiring, integrating, and using knowledge provided by both airborne and ground-based measurements were developed, with the goal of supporting decisions made in the air and on the ground. Emphasis was placed on producing concepts for air traffic management and control that are both adaptive and robust. To this end, a theoretical basis for the

IAAS was identified by incorporating principles of artificial intelligence and control theory. This concept is called *Air Traffic Management as Principled Negotiation Between Intelligent Agents*.

1.2 Wake Vortex Encounter

Research was conducted on the dynamics and control of following-aircraft response to leading-aircraft wake vortices. *Aerodynamic models for subsonic jet aircraft* exposed to vortical flows were developed, concentrating on the resultant forces and moments arising from vortical wind velocity distributions. *Hazard-factor metrics* that characterize envelopes for safe flight, assuming normal piloting actions, were identified. *Methods for designing feedback control logic* that uses available control power to minimize the disturbance to the following aircraft's flight path were derived

2. SUMMARY OF RESULTS

2.1 Advanced Air Traffic Management: The Intelligent Aircraft/Airspace System

Principled negotiation coordinates the actions of agents with different interests, allowing distributed optimization. In principled negotiation, agents search for and propose options for mutual gain. If the other agents agree to the proposal, it is implemented. Under certain conditions, an agent can search for options for individual gain without impacting other agents. In these cases, the agent can negotiate with a coordinator, rather than obtain agreement from all other agents. Principled negotiation allows agents to search options that would not be available otherwise, improving the utility function of all agents. Applied to air traffic operations, principled negotiation allows much greater freedom for optimization by system users while maintaining safety.

The ground-based air traffic control (ATC) system was created to ensure the safety of flights operating in controlled airspace. Aircraft are separated by a combination of procedures and tactical maneuvering instructions. As air traffic has grown, the ATC system has increasingly depended on computer systems. Computers now not only process radar and flight plan data, but also help controllers to manage flow, avert conflicts, and maneuver traffic.

Today's ATC system has many problems that are characteristic of traditional control systems for large-scale industrial systems. To manage the growing amount of air traffic, ATC computer systems are becoming more complex, increasing expense and making new systems more difficult to introduce. In addition, the aircraft/airspace system is not responsive to the desires of users (aircraft and operators). The procedures and actions of the ATC system prevent users from dynamically optimizing their operations and causes many hours of delays.

Distributed artificial intelligence deals with small, simple systems working cooperatively to better control large-scale systems. In multi-agent systems, each agent has its own goals, and it must anticipate the actions of other agents and coordinate actions to meet these goals. The aircraft/airspace system is a collection of agents, each with its own goals and interests. Agents include aircraft, operators, and traffic management agents. Each agent makes decisions and takes actions that affect the air traffic process. Their actions interact because aircraft must stay safely separated. Until recently, only the ATC system had sufficient data (on traffic, flight plans, and the weather) and sufficient computing power to analyze the situation. Now, airlines and aircraft also have powerful computer systems, and they can access large amounts of data from their own sensors and through high-bandwidth communications. They are also capable of making declarative decisions regarding the traffic situation.

None of the existing coordination methods solve the problems of the aircraft/airspace system. Centralized coordination schemes do not improve the ability of each agent to optimize its own operations. The game-theoretic approach allows better optimization at the expense of poorer coordination. In an AAS, good coordination is critical to avoid accidents. A new method of coordination is required that ensures safety, provides agents with greater freedom to optimize, and overcomes the problems of today's aircraft/airspace system.

The compatibility of the agents' actions can be assured if their actions are defined by a plan that is either explicitly agreed upon by all agents or checked by a coordinating agent. If agents can continually amend the plan, they can dynamically optimize their operations. Such a coordination method must ensure that no agent changes the plan in a way that adversely affects other agents or creates conflicts. If agents want to make conflicting changes to the plan, the method must fairly resolve the differences. Principled negotiation between agents is proposed for this purpose.

The principal publications and presentations related to this task are [1] to [12].

2.2 Wake Vortex Encounter

Wake vortices are an outgrowth of the aerodynamic production of lift. The bound vorticity that surrounds the wing is shed principally at the wingtips or at the outboard corners of high-lift devices, producing counter-rotating eddies that persist in the wake of the aircraft. The maximum tangential velocity of each vortex may reach several hundred feet per sec, while the radius from the vortex core to the maximum is on the order of the tip chord length. The strength of wake vortices is proportional to the generated lift and, therefore, to the weight of the aircraft. Thus, the vortical flow produced by a large aircraft presents a serious hazard to smaller aircraft that may fly into the wake. The hazard is most severe on takeoff and landing, where vorticity is intensified by the slow speed of the aircraft and where aircraft tend to fly along the same path.

The hazard is reduced by increasing the spacing between aircraft. The trailing-vortex cores initially are a span-length apart, typically shrinking to steady-state spacing of about two-thirds of the span. Because the cross-axis dimensions of the disturbance field produced by the vortex pair are relatively small, the encounter hazard becomes negligible if the trailing aircraft maintains lateral or vertical spacing of a few span lengths from the trailing vortex field. Of course, the vortices convect with the wind, so there is uncertainty about their actual location relative to the generating aircraft's flight path. Vorticity dissipates over time, so the hazard is diminished by increasing longitudinal separation. In one phase of our research, the relative hazards of encounters between 125 aircraft types were assessed on the basis of aircraft weight, rolling moment of inertia, airspeed, and other configuration features. Whereas present separation standards are based on aircraft weight alone, a still-simple but scientifically more accurate basis for separation was proposed.

While avoidance is the best way of eliminating the problem, inadvertent encounters may occur, so it is of interest to define control strategies for the following aircraft that minimize the hazard. An aircraft control law, developed using dynamic inversion of the full, nonlinear equations of motion, was developed to reduce the hazard of a wake vortex encounter. Time-scale decomposition simplifies the mathematical complexity of the development, and the wake vortex effects on aircraft aerodynamics were simulated via strip theory.

The full nonlinear equations of aircraft motion were inverted, giving equations that express the control surface deflections as functions of the desired aircraft state. The inversion process is simplified by use of time-scale decomposition, wherein slowly evolving state elements, such as airspeed or roll angle, are controlled through the faster state elements, in this case the angular rates p, q, and r. The angular rates must evolve quickly enough that they can be considered constant relative to the time-scale of the slow elements' evolution, and the direct effects of ailerons, rudder, and elevator on the slower elements must be assumed to be negligible.

With four control elements -- thrust setting, ailerons, elevator, and rudder -- four slow state elements can be commanded. This controller commands airspeed, flight-path angle, heading angle, and roll angle, a useful set for the approach-to-landing maneuver. Expressing the four commanded elements as functions of thrust, p, q, and r, the inverse of the slow-time system is generated, and the angular rates necessary for achieving the command values are determined. Inverting the equations for the angular rates generates expressions for the necessary control surface deflections.

The controller is evaluated by simulating an approach to landing, with a wake vortex directly in the desired flight path. The encounter geometry is such that the airplane descends into the wake vortex pair from above and outside, at small relative flight path and yaw angles. The initial effect of this geometry is a roll away from the vortex core. Should the plane penetrate into the core, it experiences a sudden, rapid roll into the downwash region between the two vortices. Without closed-loop control, the plane is thrown irretrievably off course. Rapid recognition of this effect, combined with the ability to make full use of the control surfaces available, allows the controlled craft to regain its flight path and to continue its approach. Simulated results demonstrate the ability of the nonlinear-inverse-dynamic controller to reduce the hazardous consequences of a wake-vortex encounter.

The principal publications and presentations related to this task are [13] to [16].

3. LIST OF PUBLICATIONS AND PRESENTATIONS

1. Wangermann, J. P., and Stengel, R. F., "Air Traffic Management as Principled Negotiation Between Intelligent Agents," presented at the AGARD Guidance and Control Symposium, *Machine Intelligence in Air Traffic Management*, Berlin, AGARD-CP-538, May 1993 (published Oct. 1993), pp. 5-1 to 5-10.

2. Wangermann, J. P., and Stengel, R. F., "Principled Negotiation Between Intelligent Agents: A Model for Air Traffic Management, "*Proceedings of the 19th Congress of the International Council of the Aeronautical Sciences*, Anaheim, Sept. 1994, pp. 2197-2207.

3. Wangermann, J. P., and Stengel, R. F., "Technology Assessment and Baseline Concepts for Intelligent Aircraft/Airspace Systems," Princeton University Report MAE-2016, Feb. 1995.

4. Wangermann, J. P., and Stengel, R. F., "Optimization and Coordination of Multi-Agent Systems Using Principled Negotiation," *1996 AIAA Guidance, Navigation, and Control Conference*, San Diego, AIAA 96-3853, July 1996.

5. Wangermann, J. P., and Stengel, R. F., “Distributed Optimization and Principled Negotiation for Advanced Air Traffic Management, “*Proc. 1996 IEEE International Symposium on Intelligent Control*, Dearborn, Sept. 1996, pp. 156-161.

6. Wangermann, J. P., and Stengel, R. F., “Principled Negotiation Between Intelligent Agents: A Model for Air Traffic Management, “*Artificial Intelligence in Engineering*, Vol. 12, No. 3, July 1998, pp. 177-187.

7. Evaluation of a Cooperative Air Traffic Management Model using Principled Negotiation between Intelligent Agents, *Proc. AIAA Guidance, Navigation, and Control Conference*, Boston, Aug. 1998, pp. 20-29.

8. Wangermann, J. P., and Stengel, R. F., “Optimization and Coordination of Multi-Agent Systems Using Principled Negotiation,” *J. Guidance, Control, and Dynamics*, Vol. 22, No. 1, Jan. 1999, pp. 43-50.

9. Wangermann, J. P., and Stengel, R. F., “Air Traffic Management as Principled Negotiation Between Intelligent Agents,” Princeton University Ph.D. Thesis, in preparation.

10. Stengel, R. F., “Intelligent Aircraft/Airspace Systems,” Invited Seminar presented at NASA-ARO Workshop on Formal Models for Intelligent Control, MIT, Oct. 1993.

11. Stengel, R. F., “Intelligent Aircraft/Airspace Systems,” Invited Lecture presented at Air Transportation Management Workshop, NASA Ames Research Center, Jan. 1995.

12. Stengel, R. F., “Intelligent Aircraft/Airspace Systems,” Invited Seminar presented at Delft University of Technology and University of California, Irvine, 1998.

13. Nichols, J., “The Wake Vortex Hazard,” Princeton University, Laboratory for Control and Automation Technical Memorandum, April 17, 1994.

14. Stengel, R. F., “Aircraft Wake Vortex Separation Standards,” Invited Lecture presented at FAA/NASA Wake Vortex Program Review, DOT Volpe Transportation Systems Center, Jan. 1996.

15. Stengel, R. F., "Dangerous Encounters of an Aeronautical Kind," Invited Seminar presented at Duke University, Massachusetts Institute of Technology, Cambridge University, Delft University of Technology, and University of California, San Diego, 1998.

16. Wold, G. J., "Nonlinear Control of an Aircraft Encountering Wake Vortices," Princeton M.S.E. Thesis, in preparation.

4. LIST OF PARTICIPATING SCIENTIFIC PERSONNEL

Robert F. Stengel	Principal Investigator
John P. Wangermann	Ph. D. student. Expected date of completion: Aug. 1999
Gregory J. Wold	M.S.E.. student. Expected date of completion: Dec. 1999
Laurent Jacolin	Visiting Researcher, 1997-1998
James Nichols	Undergraduate Student, Stevens Institute of Technology. Summer Employee, 1994

5. INVENTIONS

No patents have been awarded or filed. Software programs incidental to the conduct of research were written. These programs were intended for the use of the researchers in deriving specific results. The programs are not documented for more general use.